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A REVIEW OF LATERITE STUDIES IN SOUTHERN SOUTH AUSTRALIA

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Summary

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Studies of laterite in southern South Australia are reviewed to throw light on the nature of laterite, its genesis, classification, its relationships to substrate materials and constraining sediments, its use as a morpho-stratigraphic marker and palaeoclimatic indicator, its relationships to deep weathering, and the timing of lateritisation. Evolving views of laterite as a rock unit, as an iron-rich horizon and as a weathering product are traced and processes attributed to laterite formation viz., capillarity, leaching, combinations of water table movements, leaching and capillarity, wetting and drying processes, weathering transformations of materials rich in ferrous iron, and as a lacustrine deposit are assessed. Fundamental to theories of laterite genesis are the roles of relative and absolute accumulation of iron and aluminium minerals.

In southern South Australia interpretations of landscape evolution have depended heavily on recognition of parts of an original normal laterite profile, consisting of a pallid, bleached zone successively overlain by a mottled zone and laterite, a ferruginous and/or aluminous crust. This profile has been associated with formation on a peneplain surface under a humid, but seasonally dry, tropical climate. The possible preservation of a pristine laterite surface of great antiquity in the modern landscape on uplifted peneplains has been entertained by some workers, but questioned by others. Alternatives to this approach are provided by stratigraphic investigations of polygenetic profiles, and a continual weathering model of laterite formation that results in lateral variability in the distribution of pallid, mottled and laterite materials on a surface initially with irregular topography. Interpretations of lateritised landscapes include differential dissection of a complete laterite profile on an uplifted peneplain surface, multicyclic landscapes successively lateritised and the formation and lateritisation of high level surfaces during uplift.

Evidence of laterite formation under non-tropical conditions questions the climate-laterite correlation as does the lack of reliable minerals as climatic indicators of lateritisation. Furthermore, the recognition of lateritisation occurring throughout the Mesozoic and Cainozoic restricts the usefulness of laterite as a palaeoclimatic and morpho-stratigraphic marker.

KEY WORDS: laterite, laterite profiles, ferricrete, polygenetic profiles, peneplains, deep weathering, palaeoclimatic indicators, multicyclic landscapes, morpho-stratigraphic markers.

Introduction

There is a long history of research on materials called laterite in South Australia. The general distribution of lateritic materials in southern South Australia is shown in Fig.1. Specifically, these materials include ferruginous and aluminous crusts, variably described as 'ortstein', 'ferruginous duricrust' (Lang 1965), 'duricrust' (Woolnough 1927), 'ironstone' (Teale 1918), 'ironstone cappings' (Segnit 1937), 'indurated zones', 'ironstone gravels' (Prescott 1931) and 'ferricrete' (Firman 1967a; Bourman 1969[1]; Milnes *et al.* 1985), weathered bedrock, sediments and soils, variably ferruginised, mottled and/or bleached. This paper summarises and critically comments on these definitions. Issues addressed include the diversity of interpretations concerning the nature of laterite, processes of laterite development, laterite profiles, the topographic and climatic requirements for its formation, its age, and reconstructions of, and interpretations drawn from, lateritic landscapes.

The term 'laterite' has been in the scientific literature since the publication of Buchanan (1807). David (1887) discussed the origin of laterite in the New England district of New South Wales, but did so without reference to Buchanan's work, and the term did not appear in the South Australian literature until more than 100 years after its first usage (Teale 1918). Nevertheless, features subsequently regarded as laterite were discussed by early workers under labels such as 'Desert Sandstone' (Woolnough 1927) and 'Upland Miocenes' (Tate 1879).

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[1] BOURMAN, R. P. (1969) Landform Studies near Victor Harbour. B.A. (Hons) thesis, The University of Adelaide (unpubl.).

With few exceptions, the majority of investigators in South Australia have followed the view that laterite formed as a result of intense chemical weathering in a seasonally dry tropical climate on a peneplain surface, largely during the Tertiary. These conditions favoured the development of a laterite profile comprising a leached sandy A-horizon successively underlain by laterite, a mottled zone and a pallid zone resting on unweathered bedrock (Fig.2). Generally, the present discontinuous distribution of these materials has been ascribed to differential erosion following tectonic uplift of the peneplain.

Definition of laterite

Laterite as a rock unit

Early studies of laterite in southern South Australia were undertaken by geologists, who considered laterite to be a rock or sedimentary unit and equated it with 'Desert Sandstone' (silcrete) or with terrestrial deposits referred to as 'Upland Miocenes'. For example, Tate (1879, p. lix) regarded 'evenly-bedded sandrock, mottled clayey sands and ironstone conglomerates', occupying flat-topped localities in the Adelaide foothills and within the ranges as 'Upland Miocenes'. He

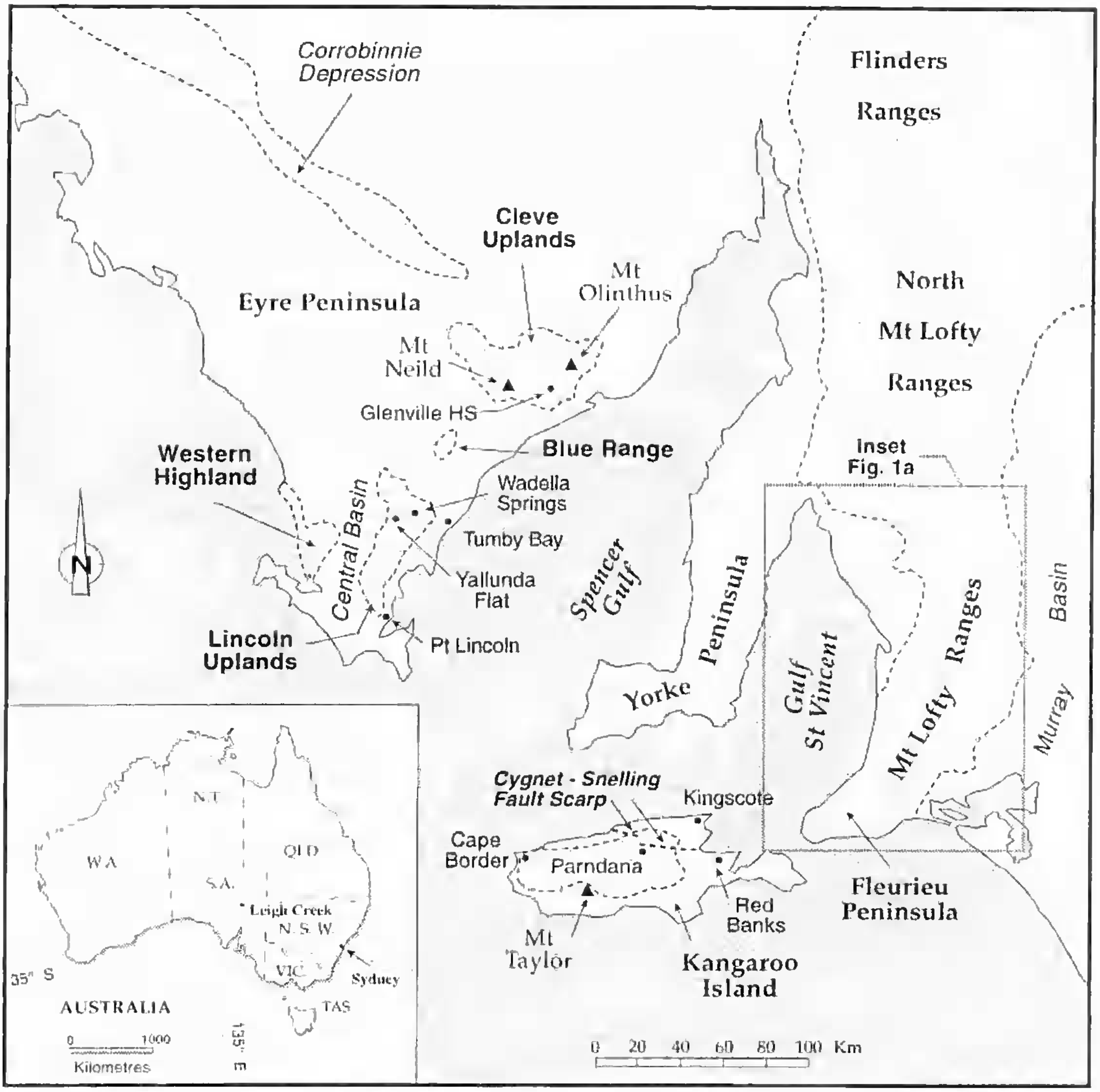
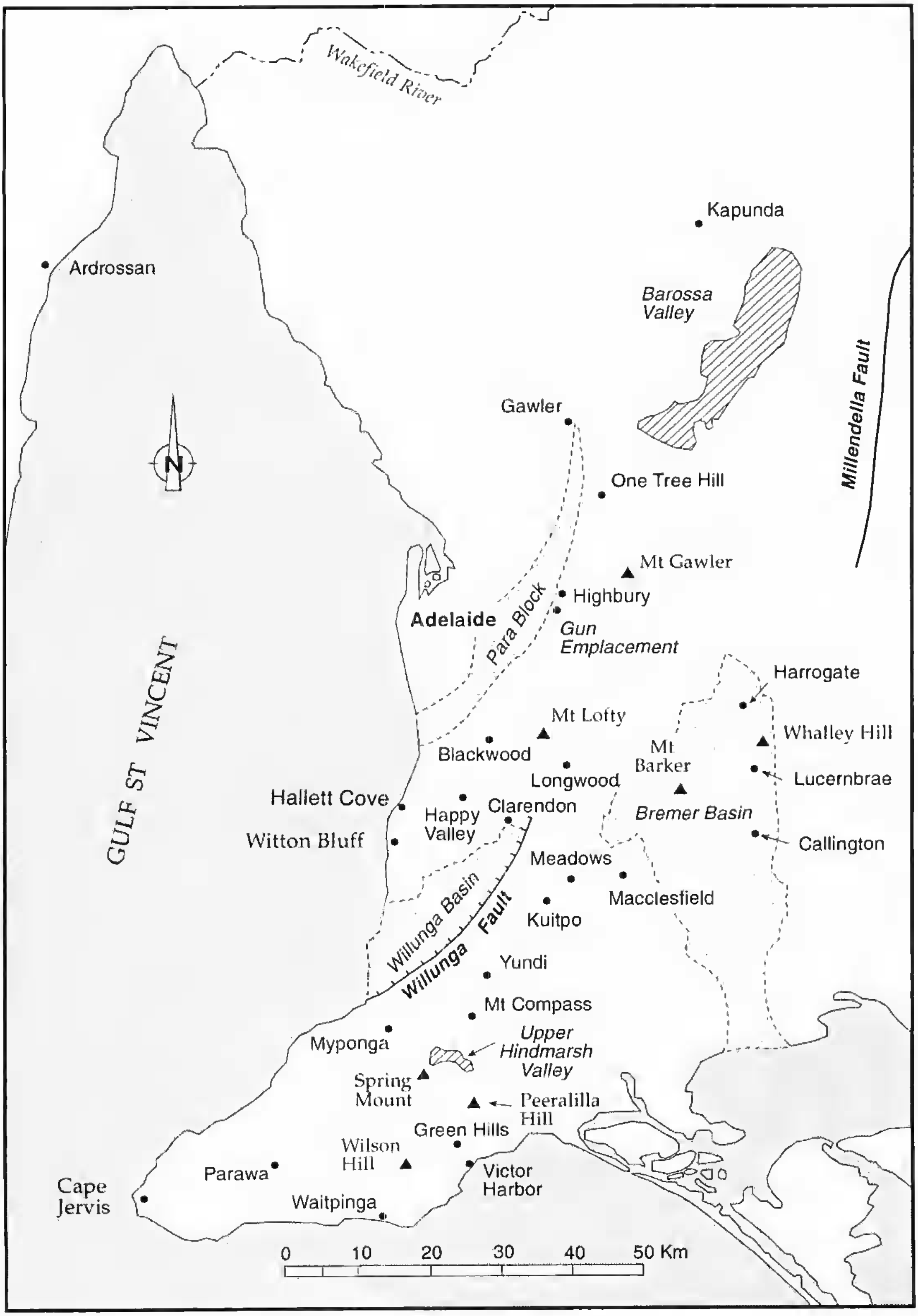


Fig. 1. Map showing the localities of lateritic areas in southern South Australia referred to in the text.

Fig. 1A. (Opposite page). Inset in Figure 1.


Wakefield River
Kapunda
Ardrossan
Barossa Valley
Millendella Fault
Gawler
N
One Tree Hill
Mt Gawler
Highbury
Adelaide
Para Block
Gun Emplacement
Harrogate
GULF ST VINCENT
Mt Lofty
Whalley Hill
Blackwood
Mt Barker
Longwood
Lucernbrae
Hallett Cove
Happy Valley
Clarendon
Bremer Basin
Witton Bluff
Callington
Meadows
Macclesfield
Kuitpo
Willunga Basin
Willunga Fault
Yundi
Mt Compass
Myponga
Upper Hindmarsh Valley
Spring Mount
Peeralilla Hill
Green Hills
Wilson Hill
Victor Harbor
Parawa
Cape Jervis
Waitpinga
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50 Km

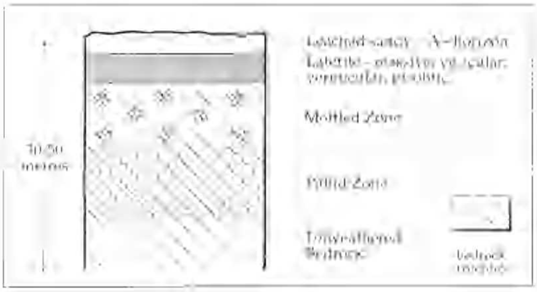

Fig. 2. Sketch of the pedogenic model of the normal or standard laterite profile incorporating a sandy, bleached A horizon above a laterite horizon, successively underlain by companion materials of mottled and bleached bedrock (Stephens 1946), considered to have developed on a peneplain under humid tropical conditions.

considered them to be correlative both with terrestrial clays overlying fossiliferous limestone at Adelaide and Tertiary terrestrial sediments bordering the Mt Lofty Ranges. Later work has demonstrated that these sediments vary in age from Pleistocene to Eocene. Furthermore, the limestone exposed in Adelaide is now known to be Late Pliocene (Ludbrook 1980) rather than Miocene as assumed by Tate.

The Desert Sandstone in northern South Australia, currently known as silcrete, was interpreted by Tate (1879) as an extensive lacustrine deposit contemporary with river gravels and sands of the Upland Miocenes. Thus silcrete and laterite were not distinguished and they were both considered to be sediments or rocks. Whereas Tate (1879) equated sediments within the ranges and on their flanks as Upland Miocenes, Benson (1906) separated them into two groups, with an older Miocene series capping hills and a younger series flanking the western escarpment of the Mt Lofty Ranges.

More recent papers have also considered laterite to be a rock unit. For example, Major & Vitols (1973, p. 46) described laterite on Kangaroo Island as a 'massive rock composed of pebble-sized pisolites of maghemite and limonite and fine-grained quartz sand cemented by limonite'. This crust, up to 1 m thick, was overlain by white, fine-grained quartz sand and underlain by mottled yellow and red clay or rocks of the weathered Kanmantoo Group metasediments. The crust occurred as boulders where ripped up by ploughs and loose pisolites, mixed with white or yellow sand, were recorded on the margins of the inland plateau.

Laterite as an iron-rich horizon

Many geological studies have been concerned with laterite in only a very incidental fashion, and almost any iron-rich horizon has been regarded as laterite (e.g. Glaessner 1953a; Olliver 1964). At various locations within and on the margins of the Mt Lofty Ranges, Tertiary sediments, variably weathered and ferruginised, have been reported to contain laterite. For example, at Happy Valley, Olliver (1964) described a sequence of Eocene marine Blanche Point Marls and North Maslin Sands overlain by Pliocene freshwater sands and clays capped and preserved by a lateritic horizon at about 200 m above sea level. The laterite consisted of a band of iron-impregnated sandy sediment. Similar occurrences were described in many sand quarries in Tertiary sands in the Adelaide region by Harris & Olliver (1964) and Olliver & Weir (1967).

Laterite as a weathering product

The association of lateritic crusts with weathering profiles (Walther 1889; Maclaren 1906) was introduced to Australian studies by Simpson (1912) and Walther (1915). They espoused the view that laterite formed as iron and aluminium oxide efflorescences were transported in solution from the water table by capillarity. Walther (1915) assigned the term 'laterite' to the complete profile.

However, laterite in South Australia has most commonly been considered to be an indurated ferruginous horizon in a weathering profile (Stephens 1946; Hallsworth & Costin 1953; Connah & Hubble 1960), which is quite different from the original laterite, described by Buchanan (1807) as a low-level sedimentary deposit consisting of massive, unstratified iron-rich clay material, full of cavities and pores, which hardened once cut into blocks and exposed to the atmosphere.

Lang (1965) followed Hallsworth & Costin (1953), restricting the term 'laterite' to crusts associated with well-differentiated profiles apparently formed by *in situ* relative accumulation of iron oxides. 'Ortstein' was used by Lang (1965) to describe crusts developed by laterally derived absolute accumulations. Where ortstein crusts formed above weathered profiles and simulated *in situ* weathering profiles they were called 'duricrusts'. Lang considered that laterites on the oldest surfaces were only occasionally developed from materials recognisable in the pallid zone, and he assumed that a discontinuous layer of Tertiary sediments overlay older rocks throughout the lateritic area. Maud (1972) also considered that only soils containing ironstones overlying mottled and pallid zones should be regarded as laterites. This definition has sometimes been ascribed the descriptor 'true laterite' (e.g. Bourne 1974[2]).

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[2] BOURNE, J. A. (1974) Chronology of denudation of Northern Eyre Peninsula. M.A. thesis, The University of Adelaide (unpubl.).

Classification of laterite

There has been little attempt to classify lateritic materials in South Australia. Teale (1918) used the term 'ironstone' to describe ferruginous materials, which were noted to affect all materials except alluvium. They were categorised into four main types: loose, concretionary gravels in deposits up to 1 m thick, iron-cemented sands and gravels, ferruginised slates and quartzites, and lateritic ironstone forming hard sheets.

Laterite was categorised by Forrest (1969[3]) as 'fossil or relict', which referred to the complete normal laterite profile, 'truncated', where the upper horizon was absent, 'immature', where the percentage of iron in the capping was low and the underlying bedrock was only partially weathered, 'derived', when the capping had been derived from the reworking of higher crusts and where this reworked capping rested on weathered bedrock, and 'ferricrete' where an iron-rich crust incorporated partially-rounded quartz pebbles and overlay fresh bedrock.

The use of the term 'ferricrete', coined by Lamplugh (1902) to describe a ferruginous conglomerate, has been extended to apply to all iron-cemented and indurated continuous horizons and crusts in preference to laterite by some workers (e.g. Milnes *et al.* 1985; Bourman 1989[4]). Ferricrete was classified by Milnes *et al.* (1987) and Bourman (1989[4]) as simple types, which included ferruginised bedrock and clastic and organic sediments, and complex types such as pisolitic, nodular, slabby and vermiform ferricrete. The different forms of ferricrete were noted to display differences in micromorphology, mineralogy and chemistry that reflect the nature of the parent material, environmental conditions during iron impregnation and subsequent transformations during landform evolution. Mottled (Fig. 3) and bleached materials (Fig. 4) were regarded as having developed independently of the ferricretes by Bourman (1989[4]).

Fig. 3. Strongly mottled zone with a crude vertical orientation in Precambrian bedrock south of Kapunda in the Mid North. Mottles (dominantly hematitic) and adjacent bleached zones display a pronounced vertical orientation. There is no overlying laterite crust.

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[3] FORREST, G. J. (1969) Geomorphological evolution of the Bremer Valley. B.A. Hons thesis, The University of Adelaide (unpubl.).

[4] BOURMAN, R. P. (1989) Investigations of ferricretes and weathered zones in parts of southern and southeastern Australia - A reassessment of the laterite concept. Ph.D. thesis, The University of Adelaide (unpubl.).

Processes of laterite formation

It is necessary for the various potential processes of laterite formation to be understood so that more reliable interpretations of ages and relationships to underlying companion materials can be provided. For example, does laterite formation require a peneplain surface, as many workers in South Australia have claimed? Furthermore, with respect to pisoliths, is it possible to distinguish formation in place from transported origins? Many theories of laterite origins have concentrated on vertical translocations of minerals in the regolith that involve capillary rise, vertical leaching and fluctuating water tables. However, Milnes *et al.* (1985) and Bourman *et al.* (1987) demonstrated that ferricrete development in southern South Australia has been almost exclusively related to lateral physical and chemical transport to, and accumulation of iron and or aluminium minerals in, discrete preferred sites.

Capillarity

Teale (1918) favoured the role of capillarity in laterite formation. He concluded that laterite formation depended upon a ferruginous rock or subsoil for an iron source, dissolution of iron, largely by organic acids, and a hot season to 'pump the iron salts' to the surface, causing oxidation and precipitation of limonite.

Laterite development by prolonged chemical weathering during the late stages of the cycle of erosion (Davis 1909, 1920), on a Miocene continental peneplain with sluggish surface drainage, in a seasonally dry tropical climate that encouraged capillary rise of iron and aluminium in solution, was described by Woolnough (1927), who had widespread experience of duricrust in Australia. He considered the 'Upland Miocenes' of South Australia to be 'veritable Duricrust albeit of somewhat aberrant type' (p. 46). He noted similarities between ferruginous cappings in the Mt Lofty Ranges with examples in Western Australia, and regarded some of the ferruginous materials on highlands as 'thoroughly typical lateritic crusts' (p. 46) and that the ferruginous surface of much of the 'Mount Lofty Plateau' was underlain by highly decomposed arenaceous rocks, similar to those related to 'Duricrust'. Laterite, 'Upland Miocenes' and 'Desert Sandstone' were thus considered as contemporary and equivalent duricrusts, resting on weathered rock materials (Woolnough 1927).

Fig. 4. Bleached and kaolinised Precambrian Aldgate Sandstone exposed by quarrying at Longwood, in the South Mount Lofty Ranges at 400 m above sea level. The depth of the section is 30 m.

The capillarity model of laterite formation should result in the reversal of soil A and B-horizons, with the surface laterite being the illuvial B-horizon and the underlying iron-depleted clay being the eluvial A-horizon. Thus, this model requires the cogenetic formation of the complete laterite profile.

Leaching

The interpretation of laterite as the B-horizon of a fossil podzolic soil was pursued by Prescott (1931) in view of evidence of the dominance of leaching of bases in laterite profiles, as opposed to capillary uplift, evaporation and surface precipitation of iron and aluminium oxides. Tropical podzolisation became the most pervasive view on laterite formation in South Australia, with the laterite horizon being regarded as a fossil illuvial B-horizon where laterite occurs in areas of aridity.

Johns (1961a) proposed that poorly drained soils on Eyre Peninsula were leached (which appears to be contradictory), during presumed humid pluvial conditions of the Pliocene, leading to the accumulation of iron oxides and the *in situ* formation of laterite.

Combinations of water table movements, leaching and capillarity

Both Whitehouse (1940) and Stephens (1946) concurred with the general podzolic origin of laterite but envisaged sources of iron not only from the overlying leached A-horizon but also from iron-depleted, weathered bedrock by water table fluctuations and capillary rise.

Hallsworth & Costin (1953) questioned that the upper podzolised layers of southern Australian laterites comprised parts of original laterite profiles, and suggested that they resulted from intense leaching after lateritisation. However, Prescott & Pendleton (1952) had pointed out that, in spite of current semi-aridity, relic podzolic soils with ironstone gravels in Western Australia remain acid, re-emphasising their hypothesis of the pedogenic origin of laterite.

The interpretation of laterite as the indurated, iron-rich B-horizon of a fossil, podzolic soil profile was favoured by Stephens (1946), who proposed a dynamic pedological model of soil formation, subsequent upon dissection of the lateritic regions in South Australia. He regarded laterite as a pedogenic material and suggested that ferruginous concretionary gravels accumulated in the soil profile in the zone of oscillating seasonal water table as a result of alternating reducing and oxidising conditions. He associated the water table fluctuations with a low relief and a humid climate. Under these conditions the concretionary gravels were assumed to form an indurated horizon by their progressive enlargement and coalescence. Later uplift and dissection of the landscape was postulated to explain the laterite mantling remnants of former peneplains. A major contribution to pedological studies was made by Stephens (1946) who recognised the influences of soil development on both the *in situ* weathered bedrock and the eroded, transported debris. This model proved to be very productive for other pedologists (e.g. Northcote 1946; Northcote & Tucker 1948; Rix & Hutton 1953).

Stephens (1971) later modified some of his views on laterite formation when he investigated a possible co-genetic relationship between silcrete and laterite. He considered that laterite formed by the accumulation of hydrated oxides, kaolinisation of mottled and pallid zones and the acidification of the whole profile, with pronounced leaching losses of silica and bases. Laterite was noted to form by both relative and absolute accumulation but he believed that relative accumulation was predominant. He also concluded that although laterite formation was associated with a fluctuating water table, it was not dependent on either perfect planation surfaces or tropical climates, views that have largely been ignored in the local literature.

Wetting and drying processes

In opposition to Prescott & Pendleton (1952), Bauer (1959[5]) favoured the view that laterite may currently be forming in southern Australia where the regolith is affected by wetting and drying. He postulated that under these conditions ferrous iron would migrate upward during waterlogging and convert to stable ferric iron in dry, oxygenating periods. He recognised a ready source of iron from decomposing country rock and a temperature regime warm enough to allow the reduction, migration and oxidation of iron.

Weathering transformations of materials rich in ferrous iron

Mawson (1907a) described a large saucer-shaped body of bog iron ore, with a maximum thickness of 10 m, forming a flattish-topped hill about 200 m above sea level at Wadella Springs on Eyre Peninsula. He concluded that the deposit had originated from spring waters, with iron sulphate having derived from the oxidation of underlying pyrite bodies. Thus Mawson, without confusing the occurrence with laterite, had observed and explained the formation of a distinctive type of ferricete.

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[5] BAUER, F. H. (1959) The regional geography of Kangaroo Island. Ph.D. thesis, Australian National University, Canberra (unpubl.).

The formation of ferruginous crusts, in such places as the Telford and Murray basins, by weathering transformations of minerals containing ferrous iron such as glauconite, siderite, chamosite and pyrite to ferric iron minerals dominated by goethite has also been recorded (Bourman 1989[4]; Bourman *et al.* 1995).

Lacustrine laterite

The view of ironstone formation as lacustrine (e.g. Fermor 1911) or swamp deposits on a peneplain surface close to sea level, with the water table close to the ground surface was suggested for South Australian samples by Segnit (1937). He also noted the occurrence of three types of ironstone cappings on high level ground and slopes in the Mt Lofty Ranges. Vesicular ferricrete, formed by iron oxide replacement of organic material in former swamp environments, has been recorded (Bourman 1989[4]) in various landscape positions in the Mt Lofty Ranges (Fig. 5) and on Kangaroo Island.

Relative and absolute accumulation: in situ *versus transported laterite*

Laterite formation by relative (*in situ*) and absolute (lateral) accumulation has long been recognised with different workers attributing differing significance to these processes. For example, Stephens (1971) attributed laterite formation dominantly to relative accumulation. Crocker (1946) agreed with the *in situ* formation of some ferruginous gravels but considered that some others have secondary origins. Milnes *et al.* (1985) and Bourman *et al.* (1987) presented evidence of dominant lateral transport in ferricrete and pisolith formation in the Mt Lofty Ranges, although the possibility of *in situ* formation was not rejected (Fig. 6). Johns (1961a) also conjectured that most of the sediment deposited on the coastal plains and Central Basin of southern Eyre Peninsula was material resorted from the uplands and included pisolitic or massive ironstone gravels. Johns believed that during lateritisation the previously peneplained basement rocks underwent deep weathering, ferruginisation and kaolinisation. Lithological variations in the basement rocks were thought to have had no influence on the final weathering products.

Maud (1972), following d'Hoore (1954) proposed absolute and relative sources of iron and aluminium oxides for the formation of laterite. The accumulation of iron and aluminium oxides was attributed either to the removal of silica and bases or their accumulation from outside sources. Well-developed lateritic ironstones on Permian glacigene sediments were explained by the concentration of iron oxides from lateral sources, whereas thinner crusts on pre-Permian rocks were ascribed to *in situ* weathering losses of silica and bases (Maud 1972). Maud (1972) believed that following landscape rejuvenation and lowering of the water table, the zones of iron-enrichment irreversibly

Fig. 5. View of bulldozer excavation on Peeralilla Hill showing ferruginous crust of vesicular ferricrete and light-coloured clays (bottom left of photograph) that include calcite and barite. This deposit of ferricrete occurs on the summit surface but below the level of surrounding hills. Borehole evidence indicates that this deposit is underlain by sandy sediments. Excavation 2.5 m deep.

hardened into lateritic ironstones. Brock (1964[6]) also agreed with d'Hoore (1954) that dissection of lateritic terrain, accompanied by lateral water movement, may have redeposited iron oxides on gentle slopes to form cappings.

Wopfner (1972) carried out an analytical investigation of mottled materials that in other contexts have been referred to as lateritic. He discussed maghemite in mottled Cainozoic sediments at Hallett Cove, where both primary and reworked maghemite were identified. Maghemite was reported from two locations: small amounts (2%) of maghemite in conspicuous red mottles, within medium grained white sandstone, were used as evidence of *in situ* formation, whereas maghemitic sub-rounded ironstone pebbles in a conglomeratic horizon were considered to be indicators of reworking. The profiles and crusts were considered to be genetically related with the conglomerate forming by reworking of an original *in situ* crust.

Many soils associated with uplifted peneplains in Australia have been noted to contain concretionary ironstone gravels, attributed by Prescott (1934) to former wetter periods when waterlogging of soils and shallow water tables were more common than at present. Chemical analyses of ferruginous gravels were interpreted by Prescott (1934) to demonstrate the concretionary character of the ironstone gravels. However, many pisoliths in southern South Australia appear to have formed dominantly by disintegration of ferruginous materials such as mottles, followed by physical transport and modifications in soils resulting in increases in iron content as well as a mineralogy dominated by hematite and maghemite (Milnes *et al.* 1987; Bourman *et al.* 1987). Transported pisoliths typically are associated with stone lines, have different chemical and mineralogical compositions to surrounding matrix materials and display multiple rinds. Milnes *et al.* (1985) also considered that ferricretes in southern South Australia, as well as pisoliths, are dominantly remnants of iron impregnated sediments, originally formed in former valley bottoms and depressions.

Fig. 6. Road cutting on the Victor Harbor-Cape Jervis road west of the Waitpinga road, exposing bands rich in pisoliths, at a depth of about 1 m, in ferruginous sandy sediments of probable Pliocene age and of aeolian origin. Other pisoliths occur at the ground surface and in the upper soil mantle. The pisoliths at depth contain only goethite, whereas those at the surface have higher iron contents and contain dominantly hematite and maghemite. Geological hammer 33 cm long.

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[6] Brock, E. J. (1964) The denudation chronology of Fleurieu Peninsula. M.A. thesis, The University of Adelaide (unpubl.).

Although there is general agreement that ferruginous materials can form both by processes operating *in situ* and those related to transportation, there has been confusion in the use of the term *in situ*. For example, some workers have considered that ferricrete, formed during landscape downwasting, which involves both vertical and lateral movement of clasts, formed *in situ*. Such ferricretes may be better regarded as residual with *in situ* weathering applying more strictly only to isovoluminous weathering (Bourman 1993b).

Laterite profiles

The normal laterite profile

Throughout the South Australian literature, following Stephens (1946), runs the thread of the normal laterite profile, which has influenced many palaeo-climatic and palaeo-environmental reconstructions. Only rarely have studies departed from this model. The normal lateritic profile (Stephens 1946), was envisaged as essentially a podzol with A, B and C horizons of eluviation, illuviation and weathering, with an accessory laterite horizon usually above a clayey B-horizon. Occasionally several lateritic horizons were noted in one profile. Stephens believed that the normal laterite profile was restricted to southern Australia; in Queensland laterite was thought to occur as an horizon in red earth profiles (Bryan 1939; Whitehouse 1940), which contained silicified zones, suggesting the incomplete removal of dissolved silica.

The model presented by Stephens has considerable merit as it emphasises the dynamic nature of landform change and pedogenesis. However, its dependence on the widespread occurrence of a former normal laterite profile related to former regional water table fluctuations, is unrealistic and has led to simplistic explanations of landscape development. Furthermore, there are various objections to the view that the original laterite is the illuvial horizon of a fossil podzolic soil.

Widespread lateritic soils on the elevated peneplain of Kangaroo Island, the Mt Lofty Ranges, Yorke Peninsula and Eyre Peninsula were reported by Crocker (1946), who observed that they contained considerable percentages of loose and indurated lateritic ironstone gravels. Some of these gravels were considered to have formed *in situ*, but on dissected marginal slopes secondary origins for them were suggested. Crocker (1946) followed the view of Prescott (1931) that laterite is the fossil illuvial horizon of a tropical Pliocene podzolic soil. Thus he reiterated the then current thoughts about laterite and further promulgated the association of laterite, peneplains, tropical climates and the Pliocene (or Tertiary), thereby setting the stage for the generation of circular arguments. Sprigg (1946) concurred with Prescott (1931) and Crocker (1946) concerning laterite genesis.

The pedogenic origin of laterite was promoted by Northcote (1946) and Northcote & Tucker (1948). These workers mapped and described a relic normal laterite profile of Pliocene age, the Eleanor Sand, on the lateritic plateau of Kangaroo Island. Crocker (1946) commented that lateritic residuals on Kangaroo Island were covered by grey and white siliceous sands derived from resorted A-horizons, originally developed on Pleistocene coastal calcareous sand dunes. However, Northcote (1946) claimed that the constant ratio of coarse to fine sand throughout the profile indicated that it had formed *in situ* and that the surface had not received accessions of wind blown sand. Consequently he regarded the Eleanor Sand as a relatively undisturbed fossil soil of Pliocene age, with a lateritic horizon developed *in situ* and preserved on an uplifted peneplain. However, Mulcahy (1960) has suggested that such sand may not be fossil, but may have derived from laterite destruction, thus yielding a similar grain size analysis to that determined by Northcote. Twidale (1983) considered that this sandy A-horizon provides evidence for the preservation of an original Mesozoic laterite profile.

Rix & Hutton (1953) regarded the summit surface in the south Mt Lofty Ranges as a block-faulted, uplifted and dissected peneplain. They followed Sprigg (1946), considering that by Early Tertiary times Precambrian rocks had been reduced to a base surface and subsequently buried by a Tertiary lacustrine and marine covermass. The soil pattern suggested to them that a further cycle of erosion had removed the greater part of the covermass, leaving isolated areas of varying extents thereby creating a new peneplain, with remnants of Tertiary deposits preserved in topographic lows. They postulated lateritisation of soils on the peneplain, prior to major faulting and dissection, concurring with Whitehouse (1940) that there had been contemporaneous laterite formation throughout Australia in the Pliocene. Residual lateritic soils were only mapped on hill summits and spurs so they suggested that erosion had removed most of a lateritic sandplain following uplift and dissection.

One soil, the Yaroona Gravelly Sand, was regarded as an original laterite profile and described as a massive band of laterite 22-30 cm thick, containing water-washed grits, gravels and sands, unconformably overlying kaolinised Precambrian shales (Fig. 7). Rix & Hutton (1953) described other residual podzols in the area as exhibiting normal profiles of ferruginous, mottled and pallid zones, overlying unweathered country rock. These workers were strongly influenced in their interpretations by the normal laterite profile model of Stephens (1946) and presented a convoluted explanation of an anomalous laterite profile, preserved in a road cut south of Clarendon, in order to account for a mottled zone overlying a laterite zone. The section can also be interpreted as a geological sequence of Precambrian rocks weathered in pre-Tertiary times, and overlain by fluvial gravels, grits and sands of Eocene age (Mawson 1953). Subsequently these sediments were partially silicified and superficially stained red by small amounts of iron oxides in groundwaters. A thin grey soil with pisoliths occurs at the surface. The above example demonstrates how complex deductive arguments, within framework of the model of the normal laterite profile, were used to introduce events, for which there was no evidence, in order to explain apparently aberrant observations. Despite this, Rix & Hutton (1953) produced a detailed soil map.

In southern South Australia the normal laterite profile of Stephens (1946) has been given excessive consideration, sometimes resulting in simplistic interpretations of landscape development. This has occurred despite observations indicating great variability in lateritic weathering profiles and despite the view of Stephens (1971) that the 'normal profile' is the exception rather than the rule. Bauer (1959[5]) and Alley (1977) disagreed with the interpretation of laterite as a tropical fossil soil profile developed on a peneplain. However, their views have not been generally accepted.

Polygenetic profiles - Alternatives to the normal laterite profile

STRATIGRAPHIC APPROACH TO INVESTIGATIONS OF LATERITIC MATERIALS

Firman (1967a, b, 1976, 1981, 1994) placed weathered zones and palaeosols within a stratigraphic framework. For example, he gave formal status to ferruginised clastic sediments and bedrock weathering profiles consisting of sesquioxides of iron and forming ironstone crusts, by introducing the name Yallunda Ferricrete. The Yallunda Ferricrete was reported to exceed 1 m in thickness in its type area at high levels over interfluves of the Lincoln Uplands (Eyre Peninsula) and on remnants of old high surfaces elsewhere. The term 'ferricrete' was used to describe ferruginous layers and crusts both independent of, and in association with, weathered profiles. Firman (1976) interpreted the various zones of the so-called normal laterite profile as having formed by different processes at different times, with the profile as old as the initial transformation of the parent material.

Ferricretes in various stratigraphic situations, including ferricrete above and below Lower Tertiary sediments in the Barossa Valley, as well as ferricretes

Fig. 7. Section in road cut near Clarendon, exposing the Yaroona Gravelly Sand of Rix & Hutton (1953), showing angular unconformity with ferruginised pebbles, grits and sands of Eocene age overlying weathered, bleached and partly kaolinised Precambrian meta-siltstones. Section is approximately 3 m high.

in the highlands of the Mt Lofty Ranges and the Lincoln Uplands were recorded by Firman (1967a). He also suggested that there were equivalents of upland ferricretes in the sedimentary succession of the Murray Basin. These included oolitic siderite-rich sediments and laterite in the Early Pliocene Bookpurnong Beds, as well as ferruginous beds and cappings in the Late Pliocene Parilla Sand near the Victoria-South Australia border. Some of the ferricretes, however, have resulted from the relatively recent oxidation of pre-existing iron-rich sediments containing glauconite and siderite and cannot be used as reliable soil stratigraphic markers.

Firman (1976) considered that between Permian and Early Tertiary times, some 200 Ma, the Mt Lofty Ranges region was a land mass experiencing prolonged weathering and erosion, so that by Early Tertiary times a subdued and deeply weathered landscape had developed. Associated bleached profiles were considered to have originated in the Mesozoic. A range of different ages of weathering and lateritisation was reported. Decomposed, bleached or mottled bedrock underlying Eocene sediments was ascribed to pre-Tertiary weathering; a laterite profile developed in Eocene gravelly sands was used to indicate post-Eocene weathering; silicified and ferruginous zones in Early Pleistocene sediments, overlying older bleached zones were argued to have equivalents in laterite profiles in the adjoining uplands; and ferruginisation in carbonaceous and pyritic Eocene sediments was attributed to recent exposure and oxidation.

The work of Firman is significant in attempting to establish stratigraphic ages for different weathering features. Nevertheless, correlating weathering phases simply on shapes, sizes and colours of mottles may be unreliable, as similar weathering patterns occur in profiles of different ages. Furthermore, Firman observed modification of some profiles by later weathering, obscuring earlier weathering products. Firman apparently took no account of local environmental conditions, which may have favoured synchronous bleaching in one area and mottling in another. Various questions remain unanswered, such as what happened to the iron derived from the bleaching of the Arckaringa Palaeosol; where did the iron for the development of the San Marino Palaeosol come from; and how was it concentrated in discrete, but more-or-less uniformly distributed mottles within previously bleached bedrock?

POLYGENETIC PROFILES AND CONTINUAL WEATHERING MODEL OF FERRICRETE FORMATION

Milnes *et al.* (1985, 1987) and Bourman *et al.* (1987) combined investigations of the field relationships of ferricretes and weathered zones with micromorphological, chemical and mineralogical analyses and questioned the former development of normal laterite profiles. These studies have suggested that there was complex reworking and continuous weathering of relic landscapes since the Early Mesozoic, and that ferricretes are dominantly remnants of iron-impregnated sediments of ancient valleys or depressions. Some ferricretes may be the culmination of processes beginning in the Mesozoic but still proceeding, resulting in the repeated dissolution, break up and neo-formation of ferricretes, as well as the ongoing and current formation of mottles and bleached zones.

Some ferricretes may have developed as suggested by McFarlane (1976), who postulated ferricrete development by the surface accumulation of ferruginous materials during landscape downwasting, the formation of gibbsitic-rich zones in near-surface situations and continued development of ferricretes and bleached zones after uplift. However, some other features of her model do not fit the observations in South Australia; there is evidence for some bleached zones and mottled zones being older than the ferricretes (Bourman 1989[4]) and no evidence has been observed of progressive development of profiles, with horizons having formed from progenitors resembling those currently beneath them. An extension of this model is the continual weathering hypothesis of Bourman (1989[8], 1993a), which proposes ongoing epigenetic transformations of ferricretes and weathered zones, with rates of change influenced by climate and events such as tectonism, sedimentary burial and submergence beneath lakes and the sea.

Topographic requirements for laterite formation

Peneplain concept in laterite development

Many workers have associated laterite formation and preservation with peneplained surfaces. However, Sprigg (1946) considered it unwise to associate laterite formation with peneplanation, which implied formation over a very long period, since he believed that lateritisation occupied only a relatively short time span. This interpretation has important implications for landscape evolution as laterite formation would first require the development of an extensive planation surface. The peneplain concept of laterite development began early (Benson 1911; Mawson 1907b; Teale 1918; Woolnough 1927), and has persisted (Campana & Wilson 1954; Brock 1964[6]; Ward 1966; Twidale 1968, 1983; Maud 1972). For example, the summit surface of the Mt Lofty Ranges was interpreted as an Early Tertiary differentially uplifted and dissected 'peneplain, surmounted by monadnocks' such as Mt Lofty, Mt Barker and Mt Gawler (Benson 1911). Tate (1879) attributed the discontinuous distribution of the 'Upland Miocenes', separated by deep ravines, to extensive denudation after uplift of the ranges.

Mawson (1907b) extended the peneplain concept to Eyre Peninsula where he described peneplains in the Port Lincoln area at about 100 m and 6 m above sea level. He equated mottled clay beds underlying the lower surface with freshwater Miocene beds near Adelaide.

Some extremely perspicacious comments on the nature and formation of ferruginous materials in the south Mt Lofty Ranges were made by Teale (1918) and his work represents the most comprehensive, detailed and objective discussion of iron oxides among all of the early investigators, particularly on classification and theories of origin of ironstone crusts. Teale (1918) interpreted the summit surface of the ranges as dislocated and eroded remnants of a former extensive peneplain. Woolnough (1927) suggested that the distribution of remnants of the terrestrial Upland Miocenes agreed completely with the physiographic conditions postulated for duricrust formation i.e. a peneplain with sluggish drainage.

In the southern part of the Mt Lofty Ranges, Campana & Wilson (1954) described a planation surface at levels up to 420 m above sea level, as a pre-Tertiary peneplain, uplifted during Tertiary and Quaternary times and deeply dissected by subsequent cycles of erosion and Brock (1964^{b}) identified remnants of an ancient landsurface on the spine of Fleurieu Peninsula covering an area of 25 km^{2}; the remnants were described as having little relief and a capping of the normal laterite profile of Stephens (1946). Ward (1966) also described flat surfaces preserved on the crests and gentle back slopes of the western blocks of the Mt Lofty Ranges as relics of a pre-deformational Mt Lofty peneplain, mantled by deep weathering and laterite. Twidale (1968) described the summit surface of the Mt Lofty Ranges as a lateritised peneplain, surmounted by a few residual remnants or monadnocks.

Today the term 'peneplain' is rarely used in geomorphic literature because, among other things, it carries with it an undemonstrable, highly theoretical mode of genesis. The terms 'erosion surface' or 'planation surface' are preferred.

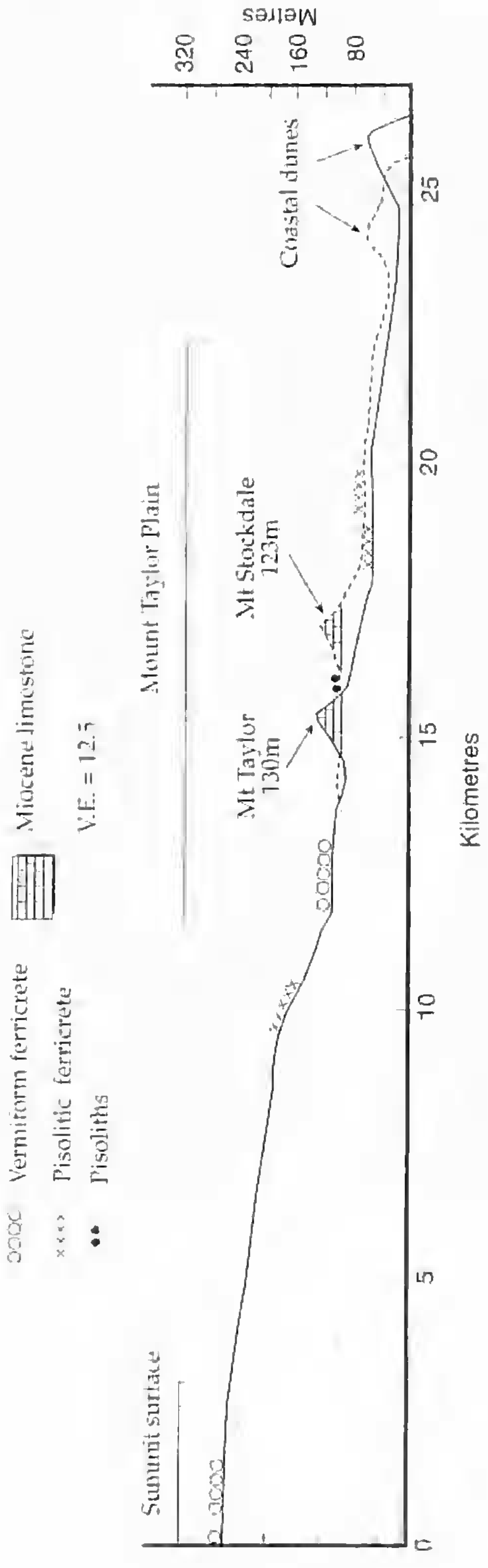
Irregular surfaces

Not all workers have considered peneplains necessary for laterite formation. If peneplain surfaces are necessary for laterite formation, the implication is that laterite formation follows peneplanation, although irregular surfaces suggest that laterite can form during, and as a result of, landscape downwasting. Some investigators such as Campana (1955) have demonstrated great complexities and irregularities in weathering and landscape evolution. Working near Gawler in the north Mt Lofty Ranges, Campana (1955) noted a leached lateritic soil overlying gneisses, schists and Tertiary fluviatile deposits resting on a pre-Tertiary weathered erosion surface. He reported gravels and coarse sands cemented by iron oxides within the Tertiary sediments. The mapping of the Tertiary (Early Eocene) strata in this area indicated that deposition occurred in a system of lakes and rivers on a weathered surface of moderate relief, above which ridges of harder rocks projected. Campana (1955) considered that the non-marine strata and older rocks had been subjected to widespread lateritisation between the Early Eocene and the Miocene. The sequence outlined by Campana (1955) illustrates pre-Tertiary weathering and bleaching of basement rocks, the deposition of Tertiary terrestrial sediments over a dissected landscape, differential ferruginisation of suitable host rocks and the inhibition of this by marine submergence.

Bauer (1959^{b}) noted that regardless of elevation, the laterite profile, the Eleanor Sand, occurs on areas of low relief and poor drainage that would have suited periodic waterlogging and drying (Fig. 8). Thus he thought that topography might have been important in assisting the formation of a distinctive soil in two differing physiographic locations, that is, on a stepped topography with flat treads, but not necessarily a peneplain.

Lang (1965) reported on soils and geomorphology of the Yundi area within the south Mt Lofty Ranges. His work represents a departure from that of many earlier workers as he invoked different types of weathering, erosional and sedimentary influences to explain the current landscape and he envisaged lateritisation and duricrust formation as proceeding over long periods of time, on landscapes of variable relief and positions above sea level. In the same area, Maud (1972) noted lateritised surfaces occurring across infilled glacial valleys and correlated them with the summit surface despite their lower landscape positions. The gentle non-tectonic inclinations of ironstone cappings were regarded as original valley morphologies, and Maud (1972) concluded that the original erosion surface was one of considerable relief.

Bourman (1989^{4}, 1993a) presented a model of laterite formation involving an original landscape of some relief that provided lateral local environmental variability. This resulted in bleaching of higher parts of the landscape and iron accumulation on plateau margins, in depressions, swamps and valley bottoms. Primary iron minerals mobilised in sub-surface zones affected by water table fluctuations were concentrated in hematitic mottles. Landscape downwasting concentrated and fragmented mottles at the surface, further weathering modified them, formed pisoliths, cemented them to form ferricrete at the surface and further modified the ferricrete. Portions of the summit surface of the Mt Lofty Ranges have been continually affected by weathering and erosion since the Permian



This suggests ferricrete formation during landscape evolution rather than being dependent on the presence of a planation surface. The continual weathering model postulates ongoing variable weathering, interrupted by tectonic activity, sedimentary burial or marine or lacustrine submergence.

Climatic conditions required for laterite formation

The vast majority of workers has equated laterite formation with a hot, seasonally dry tropical climate favouring the operation of intensive weathering processes. Low topographic relief and tropical climates were considered ideal for laterite formation, generating many circular arguments related to the laterite-tropical climate-peneplain association.

A tropical climate with pronounced wet and dry seasons, such as that of Darwin, was considered ideal for the formation of laterite by Walther (1915). This view has persisted. Stephens (1946), Sprigg (1946), Crocker (1946) and Northcote (1946) associated laterite formation with a pluvial period in the Pliocene and Johns (1961a) believed that low relief and high tropical temperatures had favoured the removal of silica, with seasonal oscillations of the water table leading to the concentration of iron oxides. More recent workers such as Bourne (1974[2]), Daily *et al.* (1974), Twidale & Bourne (1975a), McGowran (1979a), and Twidale (1976b, 1983) also favoured torrid, tropical conditions for lateritisation. The timing of lateritisation has commonly been associated with independent evidence for tropical climates. For example, Twidale & Bourne (1975a) noted that palaeontological considerations favoured the Triassic as providing the most suitable humid, tropical climatic conditions for the formation of laterite in the Mt Lofty Ranges.

In marked contrast, Firman (1981) proposed different climatic conditions for separate parts of the profiles. For example, the bleached zone of the Arckaringa Palaeosol was not considered to have been genetically associated with younger ferruginous zones but to have preceded the development of mottles and ferricretes. He ascribed bleaching to early cool climates and ferruginisation to tropical conditions.

Other workers such as Bauer (1959[5]) and Campana & Wilson (1954) considered that lateritic material might be forming at present in southern Australia so that climate for lateritisation need be no different from that of today. Maud (1972) also argued that the process of

Fig. 8. Cross section of the Mount Taylor Plain, Kangaroo Island, showing the relationships of identical vermiform ferricrete on a high pre-Miocene summit surface and a low post-Miocene surface.

iron oxide-enrichment of sediments is currently proceeding on broad valley floors in the Mt Lofty Ranges under current climatic conditions. Furthermore, there is considerable evidence of modern iron mobilisation and precipitation in southern South Australia (e.g. Bourman 1989[4]; Ferguson *et al.* 1984), so that a humid tropical climate need not be a prerequisite for bleaching and iron enrichment.

The role of climatic influences in the formation of ferruginous and siliceous duricrusts was examined by Alley (1977), who provided evidence that both laterite and silcrete formed together, for at least some time during the Tertiary, on identical strata and under similar climatic conditions, suggesting that some other factor(s) must have controlled the processes of weathering. Only the base levels of erosion differed between the silcreted and lateritised surfaces and silcrete developed on a surface, the drainage of which flowed sluggishly into Tertiary lakes. Palynological data were interpreted by Alley (1977) to demonstrate that the Eocene appeared to have been warm and temperate with a very high rainfall and that the Miocene was similar, with perhaps slightly warmer temperatures and a slightly lower precipitation. The concentration of silica at the landsurface was attributed to high alkalinity, slow groundwater movement and a high water table close to the lakes. Alley (1977) concluded that laterite and silcrete co-existed for part of the Early Cainozoic in adjacent drainage basins. Consequently, laterite and silcrete were not thought to form through the mechanism proposed by Stephens (1971) which involved the formation of silcrete by deposition of silica in dry zones after having been derived from lateritic weathering elsewhere. Furthermore, the view that laterite is associated with tropical conditions and silcrete with aridity was not supported because both formed in similar climatic and biotic regimes; only the base levels and groundwater conditions varied.

Using chemical (Hutton 1977), palynological and stratigraphic evidence to support their argument McGowran *et al.* (1978) disagreed with Alley (1977) that laterite and silcrete formed concurrently on similar rocks and under broadly similar climatic conditions from Eocene to Miocene times. However, Alley (1978) countered the arguments presented by McGowran *et al.* (1978) and made a valuable contribution to the study of laterite genesis by highlighting the influence of local topographic and groundwater conditions in its formation, as well as questioning climatic influences on laterite and silcrete development.

Minerals as climatic indicators of lateritisation

As noted above lateritisation is commonly associated with intensive weathering under tropical climatic conditions and certain minerals are suggested as indicators of climatic conditions. For example, Wopfner (1972) suggested that maghemite in mottles is a climatic indicator, originating by thermal dehydration of lepidocrocite formed by oxidation under fluctuating water table levels and warm climatic conditions. He concluded that lepidocrocite and goethite may have formed as gels that were subsequently dehydrated and crystallised as maghemite and hematite under conditions of low relief, warm climate and heavy seasonal rainfall.

However, maghemite in lateritic mottles is very rare in southern South Australia as they are dominantly hematitic (Bourman 1989[4]). Moreover, in lateritic areas of the Mt Lofty Ranges, potentially weatherable minerals including felspars, muscovite, vermiculite, chlorite and smectite have been identified (Bourman 1989[4]). In some cases there may have been neoformation of these minerals but it does seem anomalous that they should be so widespread in areas considered to have been affected by lateritic weathering processes. Previously, Crawford (1965) had noted fresh felspar gravel in mottled material at Ardrossan and used this to argue against lateritic weathering.

Palaeoclimatic indicators

Depending on the climatic conditions considered essential for laterite formation, the presence of laterite has palaeoenvironmental implications. There is little doubt that the operation of chemical processes is accelerated under hot moist conditions but there is a growing body of evidence suggesting that iron mobilisation and kaolinisation can occur under various climatic regimes - see Bourman (1993a) for a summary - so that there are considerable uncertainties linking laterite formation with a specific climate. For example, there are many reports of modern iron mobility from localities in the Mt Lofty Ranges, Kangaroo Island and Fisherman Bay (Ferguson *et al.* 1984) under current Mediterranean and semi-arid climatic conditions. These observations may also cast doubt on the reliability of correlating terrestrial ferruginous crusts with evidence of warm, humid climates derived from marine climatic indicators (McGowran 1979b).

Interpretation of lateritic landscapes

Many different hypotheses have been presented to explain the distribution and evolution of laterite. These include the development of laterite on a surface of low relief, close to sea level, followed by differential tectonic uplift and dissection of the lateritic surface, development of multiple erosion surfaces affected by episodic weathering and laterite formation, differential weathering and laterite formation on a landscape formed by uplift and dissection of a surface originally of low relief, and the weathering, erosion and sedimentation of a landscape before, during and after uplift.

Reconstruction of lateritised landscapes

The models of landscape evolution presented to explain the development of laterite depend on preconceptions of how laterite forms. For example, it is often assumed that isolated occurrences of laterite represent dissection of a former continuous laterite surface and that the different horizons of laterite profiles formed contemporaneously. In the past, many workers have tacitly assumed that the present day isolated and sporadic occurrences of laterite represent the erosional dissection of a former contiguous and uniform laterite-mantled planation surface and that these remnants are excellent and reliable morphostratigraphic markers (e.g. Twidale 1983). However, discontinuous distributions may reflect only localised formation in favourable localities (Bourman 1993a) where optimum topographic and climatic conditions did not generally prevail. Hence, the occurrence of laterite need not necessarily indicate a former extensive erosion surface.

Preservation of uplifted peneplains

Interpretations of landscape evolution have commonly depended upon recognition of uplifted and dissected former peneplains, and the preservation of parts of the original weathered surface, which can be used to reconstruct the former surface. A review of the character and age of the summit high plain of the Mt Lofty Ranges was presented by Twidale (1976b), who argued that the summit surface is of Mesozoic age and has been preserved for some 200 Ma (Twidale, 1976a). Recurrent uplift of the Mt Lofty Ranges, it was argued, postponed the ultimate degradation of the ranges by exposing new land to the area undergoing reduction. However, other workers have suggested that the best preservation of laterite is in relatively low-lying points and least in areas of greatest uplift (Milnes *et al.* 1985). The development of the Mt Lofty Ranges on an anticline, the flanks of which are faulted, was one factor used by Twidale (1976a) to explain the preservation of the laterite-capped plateau. It was maintained that the bulk of the plateau is centrally located close to the resistant compressional zone of the anticline and remnants near the western margin are buttressed by sandstone and limestone outcrops. However, the folding, which occurred in the Cambrian, was very complex and did not result in the formation of a simple anticline. Moreover, erosion of this complex structure has been so pronounced that vertical and near-vertical rock structures are exposed. Furthermore, subsequent tensional faulting has occurred within the ranges (Glaessner 1953a), so that the core of the ranges should not be considered to be in compression. The preservation of the Mesozoic sandy A-horizon of the laterite profile was thought to have assisted palaeosurface preservation by providing an absorbent cushion to protect the underlying ferruginous horizon from rainfall (Twidale 1976a). However, no evidence has been found by the present author of 200 Ma old sandy A-horizons in the ranges. Conversely, sandy soils are common, especially on Permian glacigene sediments and occur in landsurfaces, demonstrably of post-Mesozoic ages. A permeable and porous ferruginous crust of the laterite profile was also thought to render this zone resistant to erosion. However, ferruginous crusts are relatively rare and discontinuous with the thickest crusts occurring in positions well below the level of the postulated ancient surface.

Gully gravure, involving the alternation of the locus of intense erosion through the protective influence of coarse debris, was implied to reduce the rate of scarp retreat (Twidale 1976a). However, no specific sites were discussed and the present author has not observed the extensive operation of this process in the Mt Lofty Ranges. The unequal activity of rivers, which incise more rapidly than they erode laterally, was also suggested as a contributory factor in summit surface preservation (Twidale 1976a). While river incision may operate more rapidly than valley-side processes in some situations, the operation of the processes of weathering, surface wash and gullying on valley slopes and hill summits for 200 Ma has led to considerable modification of the landscape (Milnes *et al.* 1985; Bourman 1993a).

A model of landscape evolution involving increasing relief amplitude in order to account for the preservation of these presumed ancient palaeoforms was presented, and evidence supporting this model for other areas, was discussed. However, it is unlikely that the summit surface of the Mt Lofty Ranges has survived essentially unchanged for this enormous period of time.

Dissection model

The dissection model assumes relic induration at the top of former complete and continuous profiles and the lack of preservation of complete profiles is often taken to imply dissection (Stephens 1946; Thomson & Horwitz 1962; Johns 1961a, b; Maud 1972; Robertson 1974; Daily *et al.* 1974; Twidale 1983). Johns (1961a) considered that much of the Lincoln Uplands of southern Eyre Peninsula is obscured by fossil laterite and lateritic gravels and conglomerates, a formerly continuous mantle now partly stripped following regional uplift, drainage rejuvenation and erosion. Johns (1961b) also interpreted the accordance of summit levels in the eastern Mt Lofty Ranges as a base-levelled terrain of Pliocene age, carrying sporadic occurrences of ferruginous grits and laterites. He believed that once-continuous ironstone cappings of Pliocene or post-Pliocene age have been largely removed by erosion. The best exposures of ironstones were reported from "Lucernbrae" where deposits about

1 m thick were noted to mantle Kanmantoo Group metasedimentary rocks.

Maud (1972) noted that although laterite profiles in the southern Mt Lofty Ranges are typically thick, with well developed mottled and pallid zones, laterite horizons are rare. He attributed this to erosional truncation of the profile. Robertson (1974) reported ironstone fragments and deeply weathered and kaolinised rocks in the central section of the Mt Lofty Ranges at about 450 m above sea level. He also interpreted the weathered material as a remnant of a Tertiary laterite profile.

Geologists and geomorphologists have been particularly interested in laterite, primarily to establish denudation chronologies, to establish the ages of particular landforms, to correlate widely spaced planation surfaces and to throw light on the tectonic behaviour of upland areas. Examples of the use of lateritic weathering in interpreting landscape evolution are provided by the work of Sprigg (1945), Brock (1964^{6}), and Twidale & Bourne (1975a). Sprigg (1946) considered laterite formation in the Mt Lofty Ranges to be short-lived, correlated it with mottled Pleistocene sediments and believed that faulting and uplift of a peneplain occurred after laterite formation, indicating land movements of between 180 m and 300 m during the Pleistocene Kosciusko epoch of block faulting. This interpretation provides a very young age for lateritisation and faulting, whereas Brock (1964^{6}) interpreted the summit surface as a peneplain formed after prolonged subaerial weathering and erosion in the Palaeozoic, culminating in a phase of crustal stability in the Mesozoic and Early Tertiary, when lateritisation occurred prior to uplift and dissection of the surface.

Even greater antiquity of the Mt Lofty Ranges was proposed by Twidale & Bourne (1975a) who investigated the geomorphic evolution of the eastern Mt Lofty Ranges. A summit high plain (Tungkillo Surface) at 200 - 300 m above sea level, an etch surface, occasionally surmounted by scattered lateritic residuals up to 10 m high (Whalley Surface), was identified. The scattered lateritic remnants were interpreted as remnants of a once-contiguous weathered surface of low relief. The Whalley Surface and its associated deep weathering were considered to be of Mesozoic age by extrapolation from Kangaroo Island (Daily *et al.* 1974). They also argued that it developed under a humid, tropical climate. Dislocation of the Whalley Surface by faulting was proposed although there was no evidence of buried laterite on the downthrown side of the Milendella Fault. Its absence, if it ever existed, was explained by sub-surface dissolution of the iron oxides.

Kennedy model of development of lateritised surface

Twidale (1968) accounted for the absence of downfaulted remnants of the lateritised erosion surface by proposing an alternative to the traditional explanation of the summit surface of the Mt Lofty Ranges that it is an extensive lateritised surface of erosion, developed close to regional base level in the Late Tertiary, and subsequently upthrust along ancient fault lines, after which it suffered dissection. While conceding that the ferruginous crusts of the postulated laterite profile might have been removed by sub-surface solution, the possible development of an extensive landsurface in relationship to local base levels in the upper reaches, one of the possibilities suggested by the work of Kennedy (1962), was proposed. However, no critical evidence was presented to show that the summit surface of the Mt Lofty Ranges developed in this fashion.

Alternatives to truncated laterite profiles

While carrying out regional geological investigations on Yorke Peninsula, Crawford (1965) described Pleistocene deposits, exposed in the sea-cliffs at Ardrossan, as mottled dark red to olive green argillaceous sediments - The 'Ardrossan Clays and Sandrock' of Tepper (1879). He suggested that the mottling could be due to lateritisation, with the upper indurated zone having been removed by erosion and the pallid zone occurring sub-surface. However, fresh felspar gravel in the mottled material argued against lateritic weathering. Consequently, an alternative non-lateritic explanation of mottling produced by alternate wetting and drying in an environment of low relief was also suggested. Crawford (1965) obviously considered laterite within the framework of the standard laterite profile and attempted to fit his observations into it by postulating the erosional removal of an upper indurated zone. He did, however, also consider an alternative non-lateritic explanation for his observations.

The validity of accounting for incomplete profiles by erosional truncation in landscape interpretation was questioned (Bourman *et al.* 1987; Bourman 1993a) by demonstrating great lateral variability in the spatial distribution of bleached, mottled and ferricreted zones, the development of which depended closely on local micro-environments (Bourman, 1993a). Presumed remnants of laterite crusts have been shown to be lags of ferruginous mottles accumulating at the surface during landscape downwasting (Bourman 1989^{4}) and thus laterite crusts, as such, may never have existed.

Double planation theory of Fenner

Fenner (1930, 1931) presented a double peneplanation hypothesis to account for the evolution of the Mt Lofty Ranges, providing a geomorphic and tectonic framework for the use of subsequent authors. The greater part of the Mt Lofty Ranges was thought to have been stripped of an easily eroded Miocene marine covermass. He saw the double planation theory as necessary to explain transverse drainage and exhumed surfaces in the ranges. He postulated that a pre-Miocene peneplain blanketed with a Miocene marine covermass had been affected by block-faulting, tilting and differential uplift in the Late Miocene or Early Pliocene. Subsequently, this irregular surface was thought to have been peneplaned, resurrecting the older surface in places and developing a new peneplain on both Precambrian and Miocene rocks. Following this, Pleistocene (Kosciusko Epoch) tectonism renewed erosion. Some fault blocks remained buried by Tertiary sediments and others, exhumed from beneath the covermass, were subjected to renewed weathering and erosion.

Today it is generally agreed that the Mt Lofty Ranges were not totally immersed by the Miocene seas, so that the double planation theory cannot be accepted in its entirety. However, large areas of the Mt Lofty Ranges and Kangaroo Island (Milnes *et al.* 1983) were covered by Miocene seas at heights in excess of 200 m above sea level and there is evidence in the Bremer, Myponga and Upper Hindmarsh valleys that the shorelines were even higher than this (Bourman 1989[4]). Moreover, even though the covermass of marine deposits may not have totally covered the ranges, Tertiary terrestrial sediments occur extensively and at higher levels than do the marine sediments. Consequently, the double planation theory has considerable merit but it is still inadequate to account for all of the geomorphic complexities of the ranges, which have been variably exposed to processes of weathering, erosion and sedimentation for immense periods of time.

According to Sprigg (1945) laterite in the Mt Lofty Ranges formed on both a Precambrian an Cambrian bedrock undermass and a covermass of Tertiary limestones and lacustrine sediments. Initially critical of the double peneplanation theory, Sprigg (1945) subsequently made the observation that the widespread occurrence of laterite over the Mt Lofty Ranges presented a potent argument in favour of this theory.

Landscapes with multiple surfaces

Landscapes with multiple erosional surfaces have frequently been described in South Australia, with the surfaces being marked by different weathering responses. Some examples follow, which illustrate varying interpretations of multicyclic landscapes.

Bourman (1969[1], 1973[7]), identified a multicyclic landscape marked by two major erosion surfaces, the Spring Mount Plateau, developed during the time from the Mesozoic to the Eocene and the Green Hills Surface of Pliocene age on Fleurieu Peninsula. The former, underlain by a lateritic weathering profile consisting of pallid, mottled and ferruginous-rich zones, occurred at about 400 m above sea level. The surface was considered to have been tilted to the southeast. The second erosional surface 170-100 m above sea level, was capped in places by ferricrete, a term used to describe iron-cemented crusts not underlain by deep weathering profiles. The Green Hills ferricreted surface was thought to have formed from reworking of lateritic material from the summit surface. Using stranded river gravels and river profiles, Bourman (1973[7]) suggested that base level during erosion of the Green Hills Surface in the Pliocene was approximately 60 m above sea level when fluvial action modified a resurrected pre-Miocene erosion surface.

Forrest (1969[5]) examined the geomorphic evolution of the Bremer Valley in the eastern Mt Lofty Ranges and identified two erosional surfaces of low relief which he considered had formed prior to a major marine transgression in the Miocene. Consequently, both the surfaces and their associated cappings of lateritic material were interpreted as pre-Miocene in age. The Miocene sea was presumed to have transgressed an area with relief similar to that of today and lateritisation of the bedrock was presumed to have followed the development of the Whalley Hill and Lucernbrae erosion surfaces prior to the Miocene. Another surface, an exhumed one with a remnant of derived ferricrete, and thought to have formed by stripping of the Miocene limestone cover, was considered to be of Pliocene age.

In a study of landsurface development in the Mid North of South Australia, Alley (1969[8], 1973, 1977) identified remnants of a laterite surface, occurring high in the landscape but below resistant quartzite ridges. Remnants of the laterite surface were noted to be most common at stream-heads but also to occur on prominent hills that stand nearly 100 m above modern valley floors. The laterite capping of angular quartz fragments set in a matrix of iron oxides was observed to overlie severely weathered and locally kaolinitic bedrock and to be consistently thicker on lower slopes. Sections of the laterite surface were thought to have been down-faulted in the Early Tertiary and later buried by Middle Tertiary sediments. A consistently lower silcrete-capped landsurface was considered to be younger than the laterite surface.

In interpretations of multicyclic landscapes and the recognition of the ages of different landsurfaces there are inevitably many disagreements and workers in South Australia have not escaped these. An example follows. King (1976) recognised several of his world-

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[7] BOURMAN, R. P. (1973) Geomorphic evolution of southeastern Fleurieu Peninsula. M.A. thesis, The University of Adelaide (unpubl.).

[8] ALLEY, N. F. (1969) The Cainozoic History of the Mid North of South Australia. M.A. thesis, The University of Adelaide (unpubl.).

wide erosional surfaces in the Mt Lofty Ranges of South Australia. He considered that south of the Willunga Fault, 'laterite-encrusted tablelands' represented the Moorlands planation ('great Australian denudation cycle') of Late Cretaceous to middle Cainozoic age, whereas north of the fault, the Mt Lofty Ranges were thought to be surmounted by his Rolling landsurface of Miocene age that lacked a true laterite. The Widespread landscape of Pliocene age was recognised in broad valleys and basins accordant with a Pliocene coastal plain at about 180 m above sea level, and the Youngest Cycle was related to deep valleys and gorges in the ranges.

On the other hand, Twidale (1978) considered that the summit surfaces both north and south of the Willunga Fault were contiguous and of the same early Mesozoic age. However, areas of laterite mapped by Twidale (1978) north and west of the Willunga Fault on the Eden and Clarendon Blocks are variably covered with weathered and ferruginised Eocene to Pliocene sediments (Sprigg 1942, 1946; Ward 1966). In places these have been eroded to expose an underlying weathered pre-Tertiary surface, eroded and reweathered since exhumation (Sprigg 1945). Consequently, the summit surface here cannot be of early Mesozoic age. Furthermore, there may be some support for King's generalised scheme, as weathered zones have been stripped from large areas of the summit surface north of the Willunga Fault, especially in the eastern Mt Lofty Ranges (Twidale & Bourne 1975a), allowing further erosion and the potential development of a younger surface, possibly equivalent to King's Rolling surface.

Age of laterite

It is very difficult to ascribe ages to lateritic materials because they may have developed over long time periods, some may have several possible modes of genesis, others are polygenetic having been considerably reworked and reweathered, and there are severe limitations on dating techniques applied to weathered materials (Bourman 1993a). Furthermore, there are rarely constraining sediments. These difficulties are apparent in South Australia, where lateritisation has been ascribed to periods from the early Mesozoic to the present. There have been many assertions about the age of laterite in South Australia, often without presentation of convincing evidence. There has also been a tendency to prescribe a single time of lateritisation, when evidence of the timing has commonly been derived from limited study areas, from where there has often been widespread extrapolation. The following discussion of evidence presented by different workers in South Australia highlights the great variability in the ages attributed to lateritisation.

Early-Middle Tertiary

Woolnough (1927) considered that lateritisation occurred during one period, in the Miocene, and many subsequent workers have generally supported the view of a Tertiary age for lateritisation (e.g. Prescott & Pendleton 1952) but not necessarily in the Miocene. Aitchison *et al.* (1953) reported Early Tertiary lacustrine mottled sands, argillaceous sandstone and clays occurring sub-horizontally on a pre-Tertiary erosion surface in the Adelaide area, implying lateritisation in the Tertiary, and Campana (1955) favoured widespread lateritisation between the Early Eocene and the Miocene.

Sections of a laterite surface in the Mid North of South Australia were thought to have been down-faulted in the Early Tertiary and later buried by Middle Tertiary sediments, so that Alley (1973) regarded the laterite surface to be of (?)Early to pre-Tertiary age and considered that it persisted until the Middle Tertiary in the Barossa area.

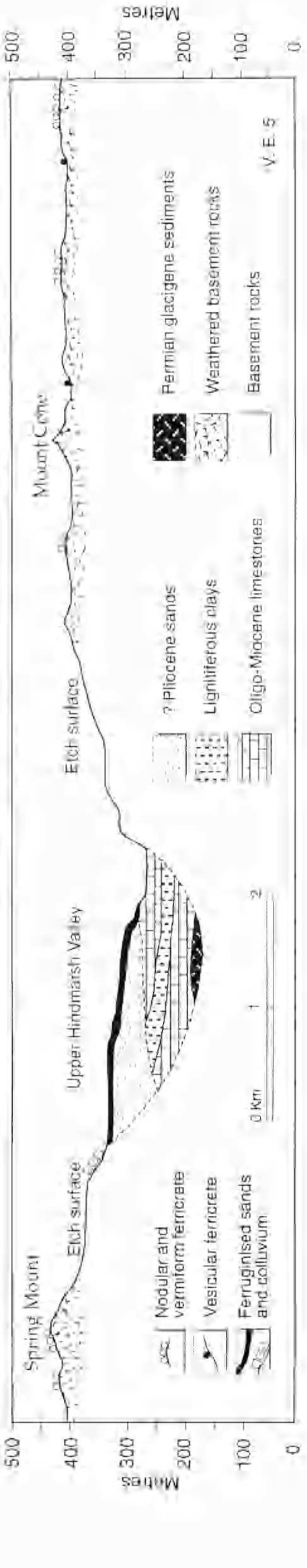
Iron-stained rounded quartz grains and ferruginous pellets were reported from within a fossiliferous marine limestone of probable Upper Eocene age (Bourman & Lindsay 1973), intersected in a drill hole at -36 m underlying part of the Waitpinga Creek drainage basin, and at an elevation of about 60 m above sea level. This observation was interpreted as indicating the development of lateritisation, or at least ferruginisation, prior to the Eocene.

Pliocene

Many concurred with Prescott (1931) and Whitehouse (1940) that there had been widespread laterite formation throughout Australia in the Pliocene (e.g. Stephens 1946; Crocker 1946; Northcote 1946; Rix & Hutton 1953; Johns 1961a, b). Fenner (1930, 1931) also implied a post-Miocene or Pliocene age for laterite in the Mt Lofty Ranges.

Working on Fleurieu Peninsula, Crawford (1959) identified laterite capping Wilson Hill at 320 m, around which an area was mapped as the lower part of a laterite profile developed on Kanmantoo Group metasedimentary rocks. The occurrence of areas of hard laterite at lower elevations (100 m above sea level), on quartzose sediments, was interpreted as indicating a very irregular original lateritised surface of Late Tertiary age. Subsequently, Bourman (1973′) demonstrated that the two occurrences were distinctive and probably of two different ages, with Miocene limestone separating the two types.

The evidence presented by Horwitz (1960) for major lateritisation in the Pliocene is also equivocal. In the intramontane Upper Hindmarsh Valley of Fleurieu Peninsula over 150 m of cross-bedded and mottled brown ferruginous sands, capped by a crust of limonite-



cemented gravels, were reported. By extrapolation these were considered to overlie fossiliferous Early Miocene limestones. The sands were thus tentatively assigned to the Pliocene. Horwitz also considered that these lateritised Pliocene sands were continuous with limonite-cemented gravels on the high plateau (Fig. 9). Thus he assigned them to the same Pliocene age. Brock (1964[6], 1971) questioned the contemporaneity of the high-level and low-level crusts and Bourman (1969[1], 1973[7]) highlighted their different characters and suggested that the higher crust was of pre-Miocene age and the lower one of Pliocene age.

Harris & Olliver (1964) reported on palynological analysis of organic material preserved in "coal balls" exposed in Tertiary sands in the Barossa Valley. The basal Tertiary unit was described as a lateritic sand and gravel overlain by laminated silty and sandy clays and was considered to be of Early Tertiary age. The clays were capped by an upper laterite. Previously the sands had been assigned to the Eocene (Glaessner 1955) or Pliocene (Hossfeld 1949) but Harris & Olliver (1964) suggested that the microfloras indicated a Miocene or possibly an Early Pliocene age for the sediments.

Twidale (1968) concluded that the deep weathering in the Mt Lofty Ranges occurred late in the Tertiary (Pliocene) and may have even continued into the early part of the Pleistocene. Major & Vitols (1973) suggested that ferruginous pisolites on the western end of Kangaroo Island were of Late Pliocene or Early Pleistocene age as an aeolian calcarenite (Middle Pleistocene Bridgewater Formation) was thought to overlie pisolites, and elsewhere blocks of ferruginous pisolite were noted to overlie marine limestone of probable Late Pliocene age.

Pleistocene

Sprigg (1946) noted similarities between mottled zones of laterite of the Mt Lofty Ranges and mottled Pleistocene clays of the nearby gulf lowland and correlated the two disparate occurrences assigning lateritisation to a humid pluvial period in the Pleistocene. Bauer (1959[5]) also favoured a Pleistocene age for lateritisation when he addressed problems associated with lateritic soils on Kangaroo Island. He noted that the Eleanor Sand, regarded by Northcote (1946) as a Pliocene fossil lateritic soil, occurs both on a Pliocene plain of marine abrasion at 50 m to 100 m above sea level (Mt Taylor Plain) and on the highest

Fig. 9 Spur-line cross section through the Spring Mount-Upper Hindmarsh Valley-Mount Cone area showing the relationships of ferricretes to Tertiary limestone. Note particularly the distribution of nodular to vermiform ferricrete and that consisting of ferruginised sands, which Horwitz (1960) regarded as of the same Pliocene age.

portions of an undissected Tertiary plateau surface at heights up to 300 m above sea level. Regardless of whether the Eleanor Sand formed in two separate periods or one, Bauer (1959^{b}) considered that both were no older than the Early Pleistocene.

Bauer (1959^{b}) also challenged the view of Prescott & Pendleton (1952) that laterite is an exposed podzolic illuvial horizon of Tertiary age, as he noted the occurrence of laterite on presumed Pleistocene surfaces. Several anomalous laterite occurrences were examined by Bauer (1959^{b}), who interpreted them to favour *in situ* laterite formation although Northcote (pers. comm. to Bauer) suggested that the ironstones had been derived by transport and could not have formed *in situ* because of the small amounts of associated clays. However, Bauer (1959^{b}) doubted this explanation on age and topographic grounds. Subsequent work (Milnes *et al.* 1983) revealed that the critical limestones used by Bauer (1959^{b}) to date the laterites are older than he thought. Consequently, many of his objections to transported origins for the laterites may be removed.

Lateritisation has also been ascribed to the Pleistocene by Horwitz & Daily (1958), Crawford (1965) and Wopfner (1972) who described mottled Pleistocene sediments in various locations.

Multiple periods of lateritisation

A detailed stratigraphic study by Glaessner (1953b) and Glaessner & Wade (1958) on the western margin of the Mt Lofty Ranges allowed them to suggest several periods of lateritisation, provide information on the character and timing of tectonic activity and to elucidate aspects of landscape evolution. Rocks and sediments of Precambrian, Cambrian, Permian and Tertiary ages were noted to be variably lateritised or to contain blocks of laterite. However, many of the iron oxides within these sediments attributed to lateritisation may have formed since exposure, in recent times, by oxidation of primary iron minerals such as glauconite and siderite.

Several groups of workers have considered that lateritic weathering has proceeded over long periods of time. For example, Campana & Wilson (1954) attributed lateritisation to Pliocene to Recent weathering, Brock (1964^{b}) from Mesozoic to the Early Tertiary and Firman (1981) observed weathering affecting materials varying in age from the Proterozoic to the Pleistocene. Milnes *et al.* (1985) considered that weathering has been ongoing since the Permian.

After investigations on Fleurieu Peninsula and in the Mid North, Horwitz (1960, 1961) considered evidence relating to the nature and age of laterite, which suggested two major periods of lateritisation, in the pre-Eocene and Pliocene. Bourman (1973^{a}) also presented evidence for two ferruginous duricrusts of different ages, one on the summit surface and the other on the sands that overlie Miocene limestone in the Upper Hindmarsh Valley. Previously, Horwitz (1960) had regarded these crusts as contiguous and of the same Pliocene age. Bourman (1973^{a}) also favoured the view that deep weathering proceeded after summit surface uplift.

Ward (1966) believed that the peneplain of the western Mt Lofty Ranges is not of the same age everywhere and was no younger than the Early Pliocene. Relationships between soil morphologies and degrees of lateritisation of materials were noted, as were well-developed lateritic mottled zones formed beneath surfaces attributed to the Late Pliocene, Early Pleistocene and Late Pleistocene. In contrast, Maud (1972) noted scattered erosional remnants of laterite surviving above the level of Miocene limestones deposited in partly exhumed glacial valleys. This suggested that the laterite surface pre-dated the Miocene, by which time it was being destroyed. Consequently, Maud (1972) believed that faulting and tilting of the lateritised surface had occurred earlier than the Pleistocene age favoured by Sprigg (1942), with the lateritised surface antedating the major period of diastrophism. He equated the surface with the Australian Surface of King (1962). Furthermore, Maud (1972) interpreted outcrops of lateritic ironstone at various levels in the landscape as relics of episodic lateritisation, affecting alluvial sediments, including reworked crusts, on former broad valley floors. He suggested that the ironstone terrace remnants varied in age from Pliocene for the highest to Recent for the lowest. These valley ironstones were described as forming parts of typical laterite profiles, with bleached, though rarely kaolinised, pallid zones.

Mesozoic

Daily *et al.* (1974) argued that evidence on Kangaroo Island enabled direct and precise dating of the laterite developed on the uplifted planate summit surface of the Mt Lofty Ranges. They described Kangaroo Island as a dissected, tilted and block-faulted plateau with a caprock of laterite, in places, breached by faults. Adjacent lowlands were noted to be essentially coincident with Permian glacigene sediments that were also lateritised and overlain by basalt of Jurassic age.

The lateritic capping of the summit plateau surface of Kangaroo Island was described as part of a laterite profile and they explained the lack of a complete laterite profile in the Late Palaeozoic sediments beneath the basalt by erosion of the ferruginous horizons prior to basalt extrusion. No evidence of deep weathering on the basalt was observed during their investigations. Consequently, they ruled out the possibility of the surface on the basalt being an etch surface.

They argued that as the basalt is of Middle Jurassic age, both the laterite and the summit surface must be older. The laterite was regarded as an indicator of a humid tropical climate and as a reliable morphostratigraphic marker. Using stratigraphic and palaeoclimatic evidence they suggested that the summit surface was eroded and lateritised during the Late Triassic, Early Jurassic, or both. Support for this conslusion was derived from evidence of warm, humid conditions associated with the Triassic flora of Leigh Creek, in the Flinders Ranges, and evidence of tectonism and uplift of a deeply weathered kaolinised zone during the Mid-Jurassic, which had led to the development of the Polda Basin on Eyre Peninsula and the extrusion of the Kangaroo Island basalt.

A Middle to Late Tertiary age for the lateritised surface was preferred by Northcote (1979) who considered that the correlation of the summit surface weathering with that beneath the Jurassic basalt was unresolved.

Schmidt *et al.* (1976) presented palaeomagnetic evidence that required sub-basaltic weathering during a Late Oligocene to Early Miocene period of dominant lateritic weathering. Idnurm & Senior (1978) favoured a synchronous Australian-wide laterite remagnetisation over this period during a major weathering event. The superimposition of a Mid-Tertiary weathering event on the earlier weathering profile was accepted by Daily *et al.* (1979) but they also presented further evidence for deep lateritic pre-Eocene weathering., Milnes *et al.* (1982) also pointed out problems with the sub-basaltic weathering hypothesis, including the preservation of a sharp basalt/weathered zone contact, the absence of leaching or kaolinisation of the basal basalt, and the fact that the basalt everywhere is largely unweathered.

Subsequent isotopic dating of kaolinite (Bird 1988[9]) and alunite (Bird *et al.* 1990), collected by the present author from the sub-basaltic weathered zone at Kingscote, together with kaolinised bedrock from the summit surface of Kangaroo Island and Fleurieu Peninsula suggests that the kaolinitic weathering beneath the basalt is of Early Mesozoic age, but that the summit surface kaolinite samples are of Middle Tertiary age. Furthermore, the alunite is not synchronous with the pre-Jurassic weathering but possibly relates to the posulated Middle Tertiary iron mobilisation of Schmidt *et al.* (1976). This illustrates the complexities involved in some weathering materials and highlights potential dangers in extrapolating even over quite short distances, and especially interregionally (e.g. Bourne 1974[2]; Twidale & Bourne 1975a, b; Twidale *et al.* 1976; Twidale 1983).

The many conflicting views on the age and development of lateritic materials, largely arise from investigations in isolated localities and extrapolation from them over sub-continental areas. These apparent conflicts may be resolved by the application of the ongoing weathering hypothesis.

Ongoing weathering

The evidence presented for a wide variety of possible ages for lateritisation and reworking of ferruginous materials in southern South Australia, ranging throughout the Mesozoic and Cainozoic including the present (see Fig. 2 in Bourman 1993b), prompted Bourman (1989[4], 1993b) to propose continual lateritic development interrupted by geological events and ongoing transformations of ferricretes over long periods of time. There may have been some times when weathering was more extreme but there is no reliable evidence of discrete and episodic periods of lateritisation.

Laterite as a morphostratigraphic marker

Duricrusts including laterite have been widely used as morphostratigraphic markers for dating and correlating land surfaces, in some cases of continental extent. Some workers, such as Twidale (1983) regard duricrusts as excellent morphostratigraphic markers and Firman (1981) considered that original materials, now ferricreted, have separate lithostratigraphic status and that continuous sheet ferricrete has both rock and soil stratigraphic status. However, there are difficulties in using duricrusts as morphostratigraphic markers. For example, they may take long periods of time to form so that any correlation would be extremely coarse. Furthermore, as noted in the section on the ages of laterites, even short distance correlation of apparently similar materials can be unreliable.

Horwitz (1960) used lateritic materials in morphostratigraphy when he associated glazed pisolites, pebbles and limonite pisolites with a pre-Tertiary surface on Fleurieu Peninsula, after observing similar ferruginous materials elsewhere beneath Tertiary limestone. However, the correlation of ferruginous materials, which superficially appear similar, may not be reliable. For example, a surface in the lower Hindmarsh Valley, carrying alleged Early Tertiary pisoliths could not have developed until post-Miocene times (Bourman (1973[7]) as it had been covered by the Miocene seas. Moreover, the occurrence of pisoliths in reworked Early Tertiary sediments is not a critical indicator of their maximum possible age. They may be of variable ages, or be older clasts reincorporated into younger sediments. In addition, it appears that some of these pre-Eocene ferruginous materials represent the transgressive marine Compton

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[9] BIRD, M. J. (1988). An oxygen- and hydrogen-isotope study of laterites and deep weathering. Ph.D. thesis, Australian National University, Canberra (unpubl.).

Conglomerate (Oligocene) of the Murray Basin (Ludbrook 1961; Lindsay & Williams 1977), and do not relate to exposure in a terrestrial environment.

A useful and innovative approach to morphostratigraphy was reported by Wopfner (1972) who recorded identical mottled profiles from the Mid North and the South East regions of South Australia, where maghemitic mottled profiles in Cainozoic sediments were capped by brown ferruginous and maghemitic crusts. Maghemite was regarded as a climatic indicator and as presenting opportunities for correlation of the Cainozoic sediments.

Twidale and co-workers (e.g. Twidale *et al.* 1976; Twidale & Bourne 1975a, b; Bourne 1974^{2}; Twidale 1983) have used duricrusts extensively as morphostratigraphic markers in southern Australia. For example, Twidale *et al.* (1976) described eight palaeosurfaces on Eyre Peninsula. Among these was an epigene surface of low relief (Lincoln Surface) protected by a lateritic duricrust and formed under humid tropical climatic conditions during the early Mesozoic. A younger surface characterised by a ferruginous duricrust was ascribed to the Late Tertiary. These surfaces were used as evidence for the progressive exposure of inselbergs on Eyre Peninsula. The Lincoln Surface was regarded as a laterite-capped dissected peneplain formerly contiguous with summit surfaces in the Mt Lofty Ranges and on Kangaroo Island and disrupted by faulting.

However, the summit surface of Blue Range described by Bourne (1974^{2}) and Twidale *et al.* (1976) as the most northerly occurrence of a postulated Mesozoic true laterite surface, and equivalent to summit surfaces on the Lincoln Uplands, Kangaroo Island and the Mt Lofty Ranges was thought to have no continuous laterite profile beneath it (Bourman 1989^{4}). Near-horizontal Precambrian metasediments are bleached and mottled but the mottles were interpreted as superficial stains of iron oxides (Bourman 1989^{4}). Tabular blocks of iron-stained and iron impregnated sandstone litter the surface and superficially resemble a crust but they were considered to be remnants of flat-lying strata within the Precambrian bedrock. Furthermore, fringing the highest sections of Blue Range, are bleached Precambrian metasediments overlain by up to 2 m of calcareous fine earth, out of sympathy with a leached lateritic environment, and capped by a sandy grey soil containing fragments of ferruginised sandstone bedrock and glazed magnetic pisoliths. Thus the surface is a complex feature, much younger than the suggested Mesozoic age.

Pedogenic accumulations of iron oxides lacking mottled and pallid zones were reported by Twidale *et al.* (1976) at lower elevations below relics of silcrete duricrust assigned to the Middle Tertiary and thus were attributed to the Late Tertiary and correlated with similar ferricretes on Yorke Peninsula and in the southern Mt Lofty Ranges. The Glenville Surface was also mapped in the area and was regarded as an etch plain equivalent of the laterite surface.

A summary of views concerning duricrusts has been presented by Twidale (1983). Laterites and bauxites were regarded as ferruginous and aluminous members of comparable origins with similar physiographic and climatic implications, developed on contiguous land surfaces and of the same age ranges in given regions. A map of Australia was compiled, reaffirming the general peripheral distribution of laterite and an interior preservation of silcrete in arid Australia (e.g. Stephens 1971). Both primary laterite and silcrete were regarded as reliable stratigraphic markers, useful in dating landforms and landscapes.

Twidale (1983) considered that the dating of laterite, silcrete and their associated surfaces has been confused by the assumption that all relic laterites are of the same age and that primary and secondary laterites have been confused. This may have been the case in some areas, but in the Mt Lofty Ranges, Brock (1964^{6}), Bourman (1969^{1}) and Forrest (1969^{3}) clearly distinguished laterites formed in place and those developed by transport. Although some workers have stressed the influence of geomorphic processes affecting laterite development during deep weathering (e.g. Alley 1973, 1977), Twidale (1983) considered that these processes had not been given sufficient appreciation. Twidale (1983) also thought that silcrete developed mainly during the Early and Middle Tertiary, forming under warm-humid to sub-humid conditions, but is today preserved in aridity. This is in contrast to the views expressed in McGowran *et al.* (1978).

Twidale (1983) believed that during the Late Mesozoic and Tertiary much of Australia was base-levelled and this surface of low relief was deeply weathered under humid, warm conditions; laterite and bauxite formed in the marginal areas with external drainage, while silcrete developed in interior catchments. The formation of the duricrust was interpreted as having been interrupted by geologic and geomorphic events so that the duration and timing of events were not everywhere the same. Climatic conditions suitable for duricrusting were thought to have lasted for at least 60 Ma and possibly for 200 Ma and ferruginous and siliceous crusts were related to the same extended period of warm, humid climate but were separated from analogous Cainozoic development by tectonic rather than by climatic events (see also Alley 1977).

Bourman (1993b) noted that the reliability of duricrusts (ferricrete) and weathered mottled and bleached zones as morphostratigraphic markers depends on whether lateritisation has been ongoing or discrete, episodic and related to periods of intense tropical weathering. Evidence of continual weathering in southern South Australia throughout the Mesozoic and Cainozoic favours the former view. Even where lateritic materials are stratigraphically constrained there is no evidence that they relate to humid tropical conditions or that their cessation depended on climatic change rather than burial by sediments. Most commonly, there are no constraining sediments and some lateritic materials have been affected by ongoing transformations over long time periods.

Conclusions

This review of the laterite literature of southern South Australia reveals many fundamental conflicts concerning the nature of laterite, its classification, the processes of laterite formation, the relationships of horizons within laterite profiles, the topographic and climatic requirements for laterite formation, the interpretation of lateritic landscapes, the age of laterite and its viability as a morphostratigraphic and palaeoclimatic marker.

In particular, there is considerable confusion and lack of consistency about the nature of materials called laterite, these varying from superficially iron-stained sediments, without associated profile differentiation, to iron-mottled and kaolinised bedrock forming part of a weathering profile. Different types of laterite fabrics have long been recognised but until recent work (e.g. Milnes *et al.* 1987; Bourman *et al.* 1987; Bourman 1993a) there has been no recognition nor discussion of their significance. Resulting from these factors there is no precise definition of the term by many workers. Distinctively different materials have often been regarded as equivalents leading to the allocation of spurious ages for the laterites. On the basis of much equivocal evidence, the tectonic behaviour of parts of the Mt Lofty Ranges and ages of lateritisation have been implied.

Many studies have been merely coincidental to other geological investigations and others have been very broad scale geomorphic reports that have involved inter-regional correlations based on the use of laterite as morphological and palaeosol-stratigraphic markers. Until quite recently there has been a dearth of studies involving detailed chemical, mineralogical and micromorphological analyses (Milnes *et al.* 1987; Bourman *et al.* 1987; Bourman 1993a).

There has been a shackling effect on landscape interpretaion by the model of the normal laterite profile, which implies the original occurrence of a complete profile including ferruginous, mottled and pallid zones having developed by the *in situ* weathering of regolith materials. Evidence of former lateritisation has been attributed to the occurrence of weathered, bleached and mottled bedrock as well as to ferruginous crusts. Thus, often, the present distribution of lateritic materials on upland areas has been explained by the dissection of formerly continuous laterite after disruption and uplift by faulting. The absence of ferruginous and/or mottled zones has been explained by various degrees of truncation of an original and complete profile, rather than considering differential development of, and lateral variability in, the distribution of ferricretes, mottled and bleached zones, depending on local environments of formation. Surprisingly, often only the laterite crust has been reported missing, even though this is likely to be the most resistant part of the profile. Where crusts are present they are all younger than the immediately underlying materials.

The common association of laterite development with humid, tropical conditions on peneplains close to base level (sea level) has led to the development of circular arguments relating climate, topography and laterite and there have been implied or specified associations of laterite with deep weathering by most previous workers, whereas hypotheses offering alternative explanations to the view of laterite being a fossil soil profile formed on peneplains under tropical climatic conditions have failed to find general acceptance.

There have been suggestions of the age of laterite formation varying from the Mesozoic to the present. The views have been promulgated that laterite of great antiquity persists in pristine form in the contemporary regolith environment and that it is an excellent morphostratigraphic marker, thereby facilitating interregional extrapolations. This interpretation is at odds with the view that lateritic materials are demonstrably complex, polygenetic features, having been weathered and modified over long periods of time and are notoriously difficult to date. There have also been some questionable correlations of lateritic materials between remote locations, based on relatively superficial observations such as the shape, size and colour of iron oxide mottles.

As laterite formation has often been equated with humid, torrid conditions it has also been used as a palaeoclimatic indicator although some workers have considered that current climatic conditions may be suitable for its formation. There is a paucity of isotopic and palaeomagnetic data and other age dating associations, such as palynology, in demonstrating the timing of lateritisation. Clearly there is a need for far more analytical work to be carried out in the investigation of laterite in South Australia.

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